LCA Methodology

Generation of an Industry-Specific Physico-Chemical Allocation Matrix

Application in the Dairy Industry and Implications for Systems Analysis

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Abstract

Background, Aims and Scope. Allocation is required when quantifying environmental impacts of individual products from multi-product manufacturing plants. The International Organization for Standardization (ISO) recommends in ISO 14041 that allocation should reflect underlying physical relationships between inputs and outputs, or in the absence of such knowledge, allocation should reflect other relationships (e.g. economic value). Economic allocation is generally recommended if process specific information on the manufacturing process is lacking. In this paper, a physico-chemical allocation matrix, based on industry-specific data from the dairy industry, is developed and discussed as an alternative allocation method.

Methods. Operational data from 17 dairy manufacturing plants was used to develop an industry specific physico-chemical allocation matrix. Through an extensive process of substraction/substitution, it is possible to determine average resource use (e.g. electricity, thermal energy, water, etc) and wastewater emissions for individual dairy products within multi-product manufacturing plants. The average operational data for individual products were normalised to maintain industry confidentiality and then used as an industry specific allocation matrix. The quantity of raw milk required per product is based on the milk solids basis to account for dairy 'by-products' that would otherwise be neglected.

Results and Discussion. Applying fixed type allocation methods (e.g. economic) for all input and outputs based on the quantity of product introduces order of magnitude sized deviations from physico-chemical allocation in some cases. The error associated with the quality of the whole of factory plant data or truncation error associated with setting system boundaries is insignificant in comparison. The profound effects of the results on systems analysis are discussed. The results raise concerns about using economic allocation as a default when allocating intra-industry sectoral flows (i.e. mass and process energy) in the absence of detailed technical information. It is recommended that economic allocation is better suited as a default for reflecting inter-industry sectoral flows.

Conclusion. The study highlights the importance of accurate causal allocation procedures that reflect industry-specific production methods. Generation of industry-specific allocation matrices is possible through a process of substitution/subtraction and optimisation. Allocation using such matrices overcomes the inherit bias of mass, process energy or price allocations for a multi-product manufacturing plant and gives a more realistic indication of resource use or emissions per product. The approach appears to be advantageous for resource use or emissions allocation if data is only available on a whole of factory basis for several plants with a similar level of technology.

Recommendation and Perspective. The industry specific allocation matrix approach will assist with allocation in multi-product LCAs where the level of technology in an industry is similar. The matrix will also benefit dairy manufacturing companies and help them more accurately allocate resources and impacts (i.e. costs) to different products within the one plant. It is recommended that similar physico-chemical allocation matrices be developed for other industry sectors with a view of ultimately coupling them with input-output analysis.

Keywords: Allocation; dairy products; milk; systems analysis

Introduction

Many industrial processes use the same resource for different products and co-products. Whether it is electricity, fuel or cleaning chemicals, in the absence of process specific data it is often necessary to allocate such resources to different products and co-products. Waste emissions to air, water and soil may also require allocation. It is a problem routinely encountered in Life Cycle Assessment (LCA) and different approaches have been proposed due to the lack of methodological guidance on this difficult issue [1–8]. The International Organization for Standardization (ISO) provides a generic framework for conducting the allocation step in LCA (ISO 14041 [9]). Where allocation cannot be avoided, ISO recommend to partition inputs and outputs between different products in a way that reflects underlying physical relationship between them. Where physical relationships alone cannot be established, inputs may be allocated in a way that reflects other relationships. This latter allocation method is generally interpreted as allocation based on economic value but has been more liberally interpreted in LCA practice to include relationships that are not causal including arbitrary physical properties of products such as mass, volume or process energy [10]. In some cases, this allocation may coincide with allocation based on causal relationship but where it does not it will not provide reliable information [10]. Heijungs and Frischknecht [11] attempt to categorize approaches for dealing with the allocation and it is also possible to avoid allocation through system expansion as demonstrated by Cederberg and Stadig [12] for the milk and beef industry and by Kim and Dale [13] for ethanol production. Kim and Overcash [14] consider three different scales for allocation: allocation using a macroscopic, quasi-microscopic and microscopic approach.

A systematic approach to allocation has been recently been suggested by Guinée et al. [15]. The authors recommend economic allocation as a baseline method for most detailed LCA applications. Allocation using physical criteria such as mass or process energy is generally discredited for a lack of justification [16], except in attributional, non-comparative LCAs, where they may be used as a proxy for economic allocation [17]. More recently, a decision tree has been developed by Guinée et al. [18] for coping with allocation and multi-functionality: 1) determine functional flows for each process of the system under study; 2) determine multi-functional processes; and 3) classify the type of allocation. In all cases, the authors firstly recommend allocation on a physico-chemical basis (if sufficient information is available) and then to allocate remaining flows on an economic basis [18]. Guinée et al. [15,18] do not extend the work to assess the implications on the reliability of LCA results are if an economic allocation is applied instead physico-chemical allocation.

In this paper, we report on the profound affects that different allocation methods have on the results of LCA studies using a dairy manufacturing plant as a case study. Dairy manufacturing plants produce more than one product as the fat content in raw milk usually exceeds the product specification for milk powders, cheeses or fresh milk products (e.g. market milk, yoghurt or dairy desserts). The excess milk fat is normally further processed into butter or anhydrous milk fat (AMF). Dairy manufacturing plants consequently produce a wide variety of dairy products, but resource use or emissions data is typically only available on a whole of factory basis. Data collection for each unit process within the plant is resource intensive and there is typically insufficient metering to collect the required information. In addition, many of the unit processes are shared for producing different products (e.g. pasteurisation/separation or spray drying; see **Fig. 1**). Such aggregation of data poses problems when undertaking a Life Cycle Assessment (LCA) for a selected product within a multi-product setting. To compare the life cycle of one dairy product to another therefore requires determination of the material consumption and process energy (electricity and fuel) demand in addition to emissions from a plant for each product.

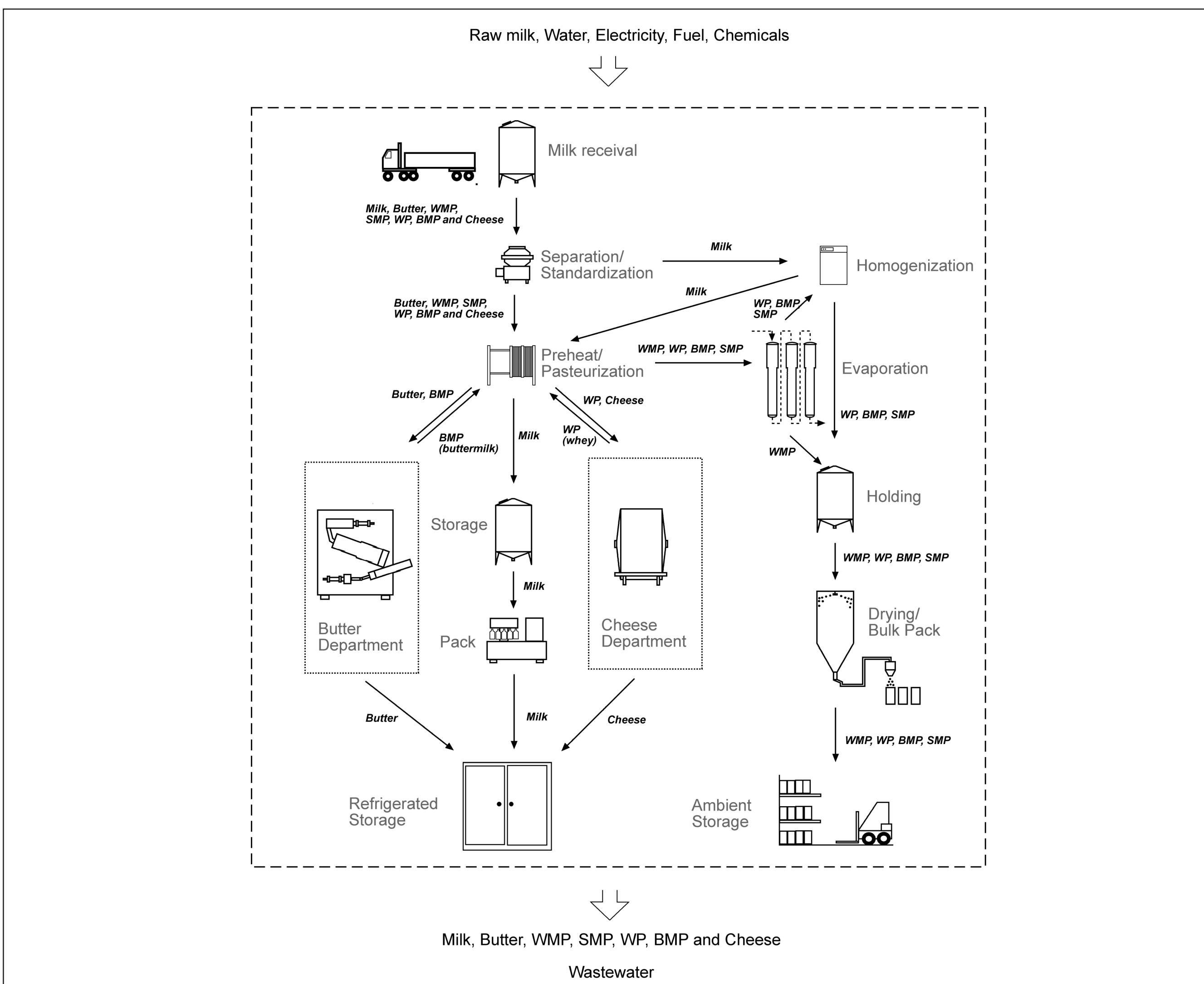

Fig. 1: Simplified schematic indicating links between products manufactured in a dairy manufacturing process (Table 3) and the unit operations within the plant

1 Methodology

1.1 ISO allocation methods

ISO 14041 differentiates between allocation principles and procedures [9] and documenting the allocation procedure is a requirement for ISO 14048 [19]. The principles indicate that allocation procedures should approximate fundamental input-output relationships and characteristics of inventory analysis. The principles may apply to multi-products, internal process energy allocation, services (e.g. transport, waste treatment) and to recycling. According to ISO 14041 processes shall be identified that are shared with other product systems and several principles shall be applied, such as: 1) the sum of the allocated inputs and outputs of a unit process shall equal the unallocated inputs and outputs of the unit process; 2) carrying out sensitivity analysis if several allocation procedures seem applicable; and 3) documentation and justification. ISO 14041 recommends a stepwise allocation procedure: 1) avoidance of allocation wherever possible by dividing unit processes to be allocated in subprocesses or expanding the product system to include co-products; 2) partitioning of inputs and outputs between multiple products or functions in order to reflect the underlying physical relationships between them if allocation can not be avoided; and 3) inputs and outputs should be allocated between multi-products and -functions reflecting each others relationship if physical relationship cannot be established. Allocation in such cases is usually based on the economic value of the products. If allocation is applied to a product system, however, it shall be applied uniformly throughout the system. Different allocation procedures are proposed for reuse and recycling systems.

1.2 Physico-chemical allocation methods

1.2.1 Allocation of raw milk to dairy products

The allocation of raw milk is important in dairy product LCAs as this step allocates upstream dairy farming processes (e.g. feed supplements, fertilizers, herbicides, water, etc) to different products. Most dairy product LCAs use an economic basis for allocating upstream and downstream processes in the absence of detailed process data [20–22]. Eide [23] uses a combination of allocation methods including biological causality, economic value and mass. Economic allocation is based on cost accounting techniques [24] and is applied to the revenue or gross margin of products. It ensures that all co-products are assigned [24] proportion of the raw milk and farming activities. The approach is not without limitations, however, as the price of a product may be a poor indicator of the actual resources used for the manufacture of the product and the subsequent environmental burden. Economic allocation is susceptible to fluctuating prices, demand, tariffs and industry subsidies. The international price of skim milk powder, for example, plunged almost 50% over a few months during 2001/2002 [25]. Such variability reflects on the allocation of resource inputs and emissions. Another approach to raw milk allocation would be to assigned farm impacts based on valuable components in the milk (e.g. on a fat or protein basis). In such cases, however, resource intensive milk by-products such as lactose powder (0% fat, 0% protein) would be assigned no environmental impact from farming activities. Also, low fat products such as skim milk, low fat yoghurt or skim milk powder would be allocated considerably lower environmental impacts than their whole milk equivalent products even though the amount of milk used in each product and level of processing is essentially the same (e.g. 26% fat for whole milk powder compared with 0.8% for skim milk powder). Allocating products using a protein equivalents basis has similar limitations in that some products (e.g. AMF) have trace levels of protein (hence assumed to have very little raw milk impacts) and other similar products have substantially different protein contents (e.g. protein enhanced versus conventional market milk) even though the mass of raw milk used in the product is similar.

In this study, the amount of raw milk is assigned on a milk solids basis, which includes fat, protein, lactose and ash, and the degree of milk solids concentration in the final product (**Table 1**). For example, the percentage of milk solids in ice-cream is 21.9% compared to 12.5% in raw milk (see Table 1). The milk solids concentration factor is therefore 21.9/12.5 = 1.8. The approach ensures that all dairy products are assigned impacts from farming activities with highly concentrated products (e.g. AMF, powders or whey protein concentrate) assigned the highest farm impacts. For example, 10,000L (10,320 kg) of raw milk can make 1001kg of cheddar cheese but also a number of by-products including 40 kg butter, 4 kg buttermilk powder (BMP) and 623kg whey powder [26]. Using the raw milk concentration factors in Table 1, it is possible to predict the total quantity of raw milk required given the mass of products and the amount of milk for each product (i.e. 1001kg*5.1 + 40kg*6.8 + 4kg*7.8 + 623kg*7.6 = 10,143 kg milk). The error using this technique is approximately 2%. Table 1 may also be used to calculate the raw milk (i.e. farm) contribution for complicated dairy products such as ice-cream where the primary ingredients are mixtures of dairy products including whey powders, buttermilk, skim and whole milk concentrates and various milk powders [27].

1.2.2 Development of an industry specific physico-chemical allocation matrix based on subtraction/substitution

An industry specific physico-chemical allocation matrix has been developed for the dairy manufacturing industry to enable better allocation of resources to dairy products given whole of plant information (**Table 2**). The allocation matrix is the product of an extensive process of subtraction/substitution to determine average resource use and wastewater emissions for individual dairy products (e.g. kL of water/tonne of yoghurt) from 17 multi-product manufacturing plants. The level of processing technology at all plants was similar. The subtraction/substitution procedure was adopted to eliminate the need for allocation and obtain a realistic measure of resource use per product. The procedure involves using initial literature and company estimates for resource efficiency per product (e.g. GJ of electricity/tonne of milk powder), normalising the resource efficiency figures for all products to milk powder, and producing a matrix of resource efficiency 'coefficients' (or allocation factors) versus dairy

Table 1: Milk concentration factors for different dairy products (for raw milk specific gravity of 1.032)

	% Milk solids	% Protein	% Fat	kg milk solids per kL of raw milk	Milk solids concentration factor	Reference
Raw milk	12.5[a]	3.1	3.9	129	1.0	[26]
Pasteurised milk	12.4	3.3	3.8	128	1.0	[47]
UHT milk	12.7	3.5	3.7	131	1.0	[47]
Cheese (Cheddar)	63.9[b]	25.3	33.8	659	5.1	[47]
WPC (65%)	95.8	63	5.6	989	7.7	[47]
WPC (35%)	95.4	36.2	2.1	985	7.6	[47]
Whey powder	95.5	12.9	1.1	986	7.6	[27]
Lactose powder	99.5	0.1	0	1027	8.0	[27]
Whole milk powder	97	27.2	26.4	1001	7.8	[47]
Skim milk powder	95.9	36.9	0.8	990	7.7	[47]
Butter milk powder	97	34.0	6.0	1001	7.8	[48]
Buttermilk	12.8	4.2	2.0	132	1.0	[48]
AMF	100	0	99.9	1032	8.0	[47]
Butter	84.4[c]	0.6	82	871	6.8	[47]
Low fat yoghurt	13.9[d]	5.9	0.2	143	1.1	[47]
Full fat yoghurt	14.2[d]	4.7	3.4	147	1.1	[47]
Ice cream	21.9[e]	3.5	10.5	226	1.8	[47]
Skim milk concentrate (for ice cream)	30	10.7[f]	0.3	310	2.4	[49]
Whole milk concentrate blend (for ice cream)	40	7.6[f]	19	413	3.2	[49]
Cream	48.1	1.9	42.8	496	3.8	[47]
Skim milk	9.3	3.6	0.1	96	0.7	[47]

[a] milk solids content assumed to be slightly higher than pasteurised milk due to higher fat content
[b] milk solids equals total solids for cheese (64.5%) less approximately 0.6% for added salt
[c] milk solids equals total solids for standard salted butter (85.1%) less 0.7% for added salt
[d] milk solids equals total solids for low fat and full fat yoghurts less approximately 0.7% for stabilizers
[e] milk solids equals total solids for ice-cream (37.2%) less 15% for sugars and 0.35% for stabilizers [49]
[f] protein content estimated as 36% of milk solids non fat (MSNF) [49]

Table 2: Industry specific physico-chemical allocation matrix for dairy products with product allocation factors (relative to milk powder)

	Raw milk	Raw milk transport	Total water use	Electricity	Fuel for thermal energy	Alkaline cleaners	Acid cleaners	Total wastewater
Milk powder	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Yoghurt	0.16	0.16	0.28	0.86	0.11	0.08	0.01	0.28
Milk	0.14	0.14	0.15	0.14	0.03	0.08	0.01	0.15
Cream	0.47	0.47	0.15	0.14	0.03	0.08	0.01	0.15
Butter	0.88	0.88	0.40	0.36	0.17	0.10	0.50	0.40
AMF/Ghee	1.05	1.05	0.40	0.36	0.05	0.10	0.50	0.40
Cheese (cheddar)	0.64	0.64	1.40	0.57	0.1	0.70	1.00	1.40
Whey powder	1.01	1.01	1.20	1.50	1.3	0.90	2.00	1.20
UHT	0.14	0.14	0.15	0.29	0.06	0.08	0.01	0.15
Ice Cream	0.23	0.23	0.68	1.92	0.004	0.90	0	0.68
WPC/Lactose**	1.00	1.00	5.82	4.52	2.75	6.26	9.97	5.82

* coefficients based on factory average resource use and wastewater emissions for different dairy products from 17 multi-product dairy manufacturing sites
** There was insufficient information to separate energy and mass flows for whey protein concentrate (WPC) and lactose. Some plants crystallize and dry lactose whereas others treated the lactose as a waste product

products (see Table 2). The coefficients were then optimised for all products using surveyed process data from the 17 plants given the constraints of the number of products, mass of different products and total resource use for each plant. For example, process energy coefficients for a plant that only produced milk powders (the cream was sent off site) was then used to update the butter process energy coefficients for a plant that only produced butter and milk powders. Once an estimate for butter was obtained, this was used to determine the AMF process energy coefficients in a plant that produced milk powders, butter and AMF, and so on. By doing this for 17 plants for many different products (using the same level of technology) a very good estimate of the average process energy figures (and resource efficiency coefficients) for different products could be obtained. The coefficients could be further refined by using an approach similar to the residual allocation system (RAS) method, used for optimizing input coefficients in input-output tables [28–31].

Electricity and fuel use figures per tonne of product were initially based on older data from Australian and NZ plants [32,33] and then iteratively updated with surveyed plant data. Note that while the Australian fuel use figures may be higher than in other parts of the world due to the comparative isolation of some of the dairy plants and the reliance on coal rather than natural gas for thermal process energy (approximately 20% of plants surveyed), the ratio between coefficients will be the same to other plants around the world provided a similar level of technology is used. Data for acid and alkali use is based on information provided by chemical suppliers and surveyed plants if available. The amount and type of packaging used for different products is usually available and does not require allocation. Acids, chemical coagulants and polymers used during wastewater treatment may be allocated using the wastewater allocation (provided the plant does not source separate the wastewater streams). Water use and wastewater emissions estimates for the different products were initially based on older literature sources [34–37] and then iteratively updated with data from the surveyed plants. A more recent study published by the Danish EPA and United Nations Environment Programme [38] reports a substantial improvement in water use since the earlier studies with the average consumption reducing from approximately 3.3 L water/kg milk [39] to 1.3–2.5 L/kg milk in the early 1990s. The results of the survey in this study from 1999–2003 give an average gross water : raw milk ratio of 1.0 L/kg milk (ranging from 0.26–2.4 L/kg) for different multi-product factories. The figure excludes plants that only process milk by-products (e.g. whey to whey protein concentrate) or plants that primarily process dairy intermediates into dairy products (e.g. milk concentrates and powders for ice cream or yoghurt production).

Recovered water (e.g. condensate) during powder or milk concentrate manufacture is not included in the wastewater emissions. This is typically a high quality water that is either reused in the boiler, lost as steam or emitted as a non-wastewater discharge. Whey is also not included in the wastewater figures, but considered a separate emission that is either further processed to whey powder, whey protein concentrate and lactose powder or disposed as a wastewater stream (i.e. needs to be added to the overall plant wastewater figures). Such treatment is necessary as there is wide variation in how different factories manage whey. Whey that is not reprocessed is often land irrigated in Australia and, in such cases, the irrigated whey fraction is then reallocated as a wastewater for all products, not just cheese. This is because the whey would be considered a total milk solids product loss from the plant that could have been used more efficiently in the production of other products (i.e. loss of protein and lactose).

The allocation matrix given in Table 2 enables the allocation of the primary resources for any combination of dairy products based on physico-chemical principles. By normalizing the coefficients to milk powder, for example, the relative resource use for each product is maintained and the allocation matrix is capable to accounting for differences in overall plant efficiency (e.g. using less efficient coal rather than natural gas for thermal process energy). Normalizing the average resource data also ensures company confidentiality. The percent allocation is determined by multiplying the annual production of a product by its unique coefficient (or allocation factor; AF given in Table 2) and then dividing by the sum of all products multiplied by its specific AF, i.e.

$$\text{Allocation}(\%)_i = \frac{\text{Production}_i \times \text{AF}_i}{\sum_{ij} \text{Production}_{ij} \times \text{AF}_{ij}}$$

The determined percentage allocation is multiplied by the input or output flow of interest, e.g. fuel use or wastewater emission. Fortunately the age and configuration of the processing technology surveyed for the different dairy plants is similar. If the technologies were substantially different ('new' versus 'old' technology), it may be necessary to classify the technologies and generate allocation matrices for different levels of technology sophistication.

2 Results and Discussion

2.1 Allocation of raw milk and farm impacts

As farm is the most important stage over the life cycle of a dairy product [20–23,40–41], the allocation of milk and its associated impacts to different dairy products is a critical step in dairy LCAs. The raw milk requirements for a typical multi-product plant are given in **Table 3** and its allocation

Table 3: Primary resource input and wastewater outputs for a model multi-product dairy manufacturing plant

Annual Inputs	Annual Outputs
Raw milk 750 ML (774 kt) **Utlilties** 140,000 GJ electricity 720,000 GJ natural gas 1100 ML water 800 tonne alkali 200 tonne acid	**Products** 100,000 tonnes/yr of market milk 30,000 tonnes/yr of skim milk powder 20,000 tonnes/yr of whole milk powder 5,000 tonnes/yr of butter milk powder 5,000 tonnes/yr whey powder 20,000 tonnes/yr of Cheddar 15,000 tonnes/yr of butter **Wastewater** 1100 ML of wastewater treated using facultative ponds and then irrigated

Table 4: Allocated inputs and outputs for the model multi-product factory given in Table 3

	Raw milk					**Water/Wastewater**				
	Allocation factor	* Product	%Allocation	kt	t milk/t	Allocation factor	* Product	%Allocation	kL	kL/t
Market milk	0.13	13,000	0.13	100,070	1.0	0.15	15,000	0.13	146,667	1.5
SMP	1.00	30,000	0.30	230,930	7.7	1.00	30,000	0.27	293,333	9.8
WMP	1.00	20,000	0.20	153,953	7.7	1.00	20,000	0.18	195,556	9.8
BMP	1.00	1,500	0.01	11,546	7.7	1.00	1,500	0.01	14,667	9.8
Whey Powder	0.98	9,800	0.10	75,437	7.5	1.20	12,000	0.11	117,333	11.7
Butter	0.87	13,050	0.13	100,455	6.7	0.40	6,000	0.05	58,667	3.9
Cheese	0.66	13,200	0.13	101,609	5.1	1.40	28,000	0.25	273,778	13.7
Total		100,550	1.00	774,000			112,500	1.00	1,100,000	
	Electricity					**Fuel**				
	Allocation factor	* Product	%Allocation	GJ	GJ/t	Allocation factor	* Product	%Allocation	GJ	GJ/t
Market milk	0.14	14,000	0.14	20,153	0.2	0.03	3,000	0.04	30,747	0.3
SMP	1.00	30,000	0.31	43,184	1.4	1.00	30,000	0.43	307,473	10.2
WMP	1.00	20,000	0.21	28,790	1.4	1.00	20,000	0.28	204,982	10.2
BMP	1.00	1,500	0.02	2,159	1.4	1.00	1,500	0.02	15,374	10.2
Whey Powder	1.50	15,000	0.15	21,592	2.2	1.30	13,000	0.19	133,238	13.3
Butter	0.36	5,357	0.06	7,712	0.5	0.05	750	0.01	7,687	0.5
Cheese	0.57	11,400	0.12	16,410	0.8	0.10	2,000	0.03	20,498	1.0
Total		97,257	1.00	140,000			70,250	1.00	720,000	
	Alkaline					**Acid**				
	Allocation factor	* Product	%Allocation	kg	kg/t	Allocation factor	* Product	%Allocation	Milk	kg/t
Market milk	0.08	8,000	0.10	76,190	0.8	0.01	1,000	0.01	2,000	0.02
SMP	1.00	30,000	0.36	285,714	9.5	1.00	30,000	0.30	60,000	2.00
WMP	1.00	20,000	0.24	190,476	9.5	1.00	20,000	0.20	40,000	2.00
BMP	1.00	1,500	0.02	14,286	9.5	1.00	1,500	0.02	3,000	2.00
Whey Powder	0.90	9,000	0.11	85,714	8.6	2.00	20,000	0.20	40,000	4.00
Butter	0.10	1,500	0.02	14,286	1.0	0.50	7,500	0.08	15,000	1.00
Cheese	0.70	14,000	0.17	133,333	6.7	1.00	20,000	0.20	40,000	2.00
Total		84,000	1.00	800,000			100,000	1.00	200,000	

Table 5: Comparison of different allocation methods for raw milk to various products in multi-product dairy manufacturing plant

	Milk solids	**Economic Jul–01[a]**	**Economic Jun–02[a]**	**Mass**	**Process energy[b]**	**Fat**	**Protein**
Market milk	13.1%	31.4%	34.5%	51.3%	6.2%	13.2%	12.1%
Skim milk powder	30.2%	20.8%	17.4%	15.4%	42.6%	0.8%	40.5%
Whole milk powder	20.1%	11.1%	10.5%	10.3%	28.4%	18.4%	19.9%
Butter milk powder	5.0%	3.5%	2.9%	2.6%	7.1%	1.0%	6.2%
Whey powder	4.9%	1.0%	1.1%	2.6%	9.4%	0.2%	2.4%
Butter	13.1%	9.5%	10.9%	7.7%	1.9%	42.8%	0.3%
Cheese	13.5%	22.7%	22.6%	10.3%	4.5%	23.5%	18.5%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

[a] based on US export prices and quantities [42]
[b] based on thermal and electrical energy inputs to manufacturing plant (Table 4)

on a milk solids basis (coefficients incorporated into the allocation matrix) to different product is given in **Table 4**. The results of six different allocation techniques are provided in Table 5 for comparison. **Table 5** includes the standard practical LCA allocation methods of economics, mass and process energy. In addition, the economic allocation is carried out for two time periods: July 2001 and one year later for June 2002. Allocation of raw milk according to routinely used LCA methods of economics, mass and process energy results in considerably different amounts of milk

being assigned to the different product. The difference is 8-fold for market milk when using mass or process energy allocations and similarly almost 6-fold for butter and 9-fold whey powder when using economic versus process energy allocation. For mass allocations, assigning over 50% of the raw milk to market milk is inappropriate for the model multi-product factory as most of the raw milk is used for the dried products. Equally, as market milk and – to a lesser degree – cheese are premium priced products relative to the level of processing or raw milk required, allocating twice as much raw milk to them relative to what is actually required for their manufacture (i.e. amount of milk solids) is problematic. Economic allocation of raw milk between July 2001 and June 2002 varies on average 10% for each product and varied up to 16% for powder for the model plant. Naturally process energy allocation skews the raw milk allocation to those products that require large amount of process energy for their manufacture (i.e. milk powder and whey powder) at the expense of products such as market milk or butter that are less energy intensive.

Dairy manufacturing is essentially a milk solids concentration process. It is therefore recommended to allocate the raw milk to products on a milk solids basis as this is a more causal physical relationship than mass or economics. Products that require no concentration (e.g. market milk) are assigned a simple proportion of the incoming raw milk (i.e. 100,000 t/774,000 t = 13% – see Tables 3 and 4). Products that concentrate milk to recover the fat (e.g. butter), protein (e.g. skim milk powder) or lactose (e.g. lactose powder) and remove water need to be assigned more of the raw milk than lower concentrated products. This is why mass allocation is particularly problematic for the dairy industry as it cannot account for the degree of raw input concentration in the products. Allocation on a protein and fat content is included in Table 5 for comparison. For products that contain moderate levels of fat and protein (e.g. market milk, whole milk powder or cheese), the allocation is similar to that for the milk solids or economic allocation but differs considerably once the protein and fat ratio varies from the raw milk norm. For example, the amount of milk allocated to butter for the model plant based on protein content basis would some 40 times less than on a milk solids basis. Hence the farm impacts for butter are heavily discounted if allocated on a protein basis. Likewise, too little raw milk (and farm impacts) would be allocated to skim milk powder if allocation were on a fat content basis. Dairy products such as lactose powder that contain neither fat nor protein would have no farm impacts if allocation were on a fat or protein basis. Considering that lactose comprises around 40% of the total raw milk solids [27] and lactose powder is valued around $US500–600 per tonne [42] it appears unreasonable not to allocate any farm impacts to this byproduct

2.2 Allocation of manufacturing resources and waste

While accurate allocation of raw milk (and hence farm impacts) to different products is a critical for dairy LCAs, allocation of energy and material inputs is particularly important for energy intensive dairy products (e.g. ultra high treated (UHT) milk and whey powders) that may have high energy related environmental impacts (e.g. human toxicity, global warming, acidification or photochemical smog formation). A comparison between the major primary inputs for different allocation techniques is given in **Fig. 2** for the model plant detailed in Table 3. The physico-chemical allocation in Table 4 can be considered a good approximation of the resource use and wastewater associated with each of the products. The allocation varies from product to product and from resource to resource. The figure clearly illustrates the limitations of assuming a fixed allocation for different resource inputs and wastewater regardless of whether the allocation is on an economic, mass or protein basis. For example, fuel use for market milk is overestimated by some 12 times on a mass basis and 8 times on an economic basis. Alternatively, fuel use during whey powder manufacturing is underestimated by approximately 7 times on a mass and 10 times on economic basis. Allocation of the amount of acid used is particularly poorly allocated using fixed allocation methods: the mass and economic allocation methods overestimate the amount of acid by some 50 and 30 times, respectively. Caustic rather than acid is primarily used for cleaning lines during milk production. Allocation using protein underestimates waster use and wastewater emission for butter by 16 times. Thus applying fixed type allocation rules for all input and outputs based on the quantity of products is introducing order of magnitude deviations from phyisco-chemical allocation in some cases making the error associated resource inventories (e.g. electricity or raw milk usage; <1%), wastewater emissions (e.g. <10%) or even truncation errors [43,44] (e.g. up to 50%) addressed through input-output analysis [45] insignificant by comparison.

3 Implications for Environmental Systems Analysis

The dairy manufacturing case study in this paper illustrates typical problems encountered when allocating resource inputs and wastewater in multi-product factory. The results raise questions about the reliability of LCA allocation techniques in complicated multi-product plants without detailed process data. Similar large differences have also been observed for petroleum refineries when allocating on process rather than aggregated level [46]. Despite having good quality whole of factory data and following ISO 14041 allocation methods, application of fixed type allocation rules for all input and outputs based on the quantity of products resulted in considerable deviations from physico-chemical allocation. While mass and process energy allocation may be discredited [16,17], economic allocation introduces similar order of magnitude sized variations in this example. System expansion is recommended to avoid co-product allocation [17] but this does not necessarily solve the raw milk allocation problem for this case study. It is suggested here that milk solids is the most appropriate causal basis for allocating raw milk to products in the dairy industry as this approach covers the wide variety of products manufactured. The allocation basis will change for other industries and if the dairy system was to be expanded to include other co-products (e.g. for allocating meat and milk on farm).

The study highlights the importance of accurate causal allocation procedures that reflect industry-specific production

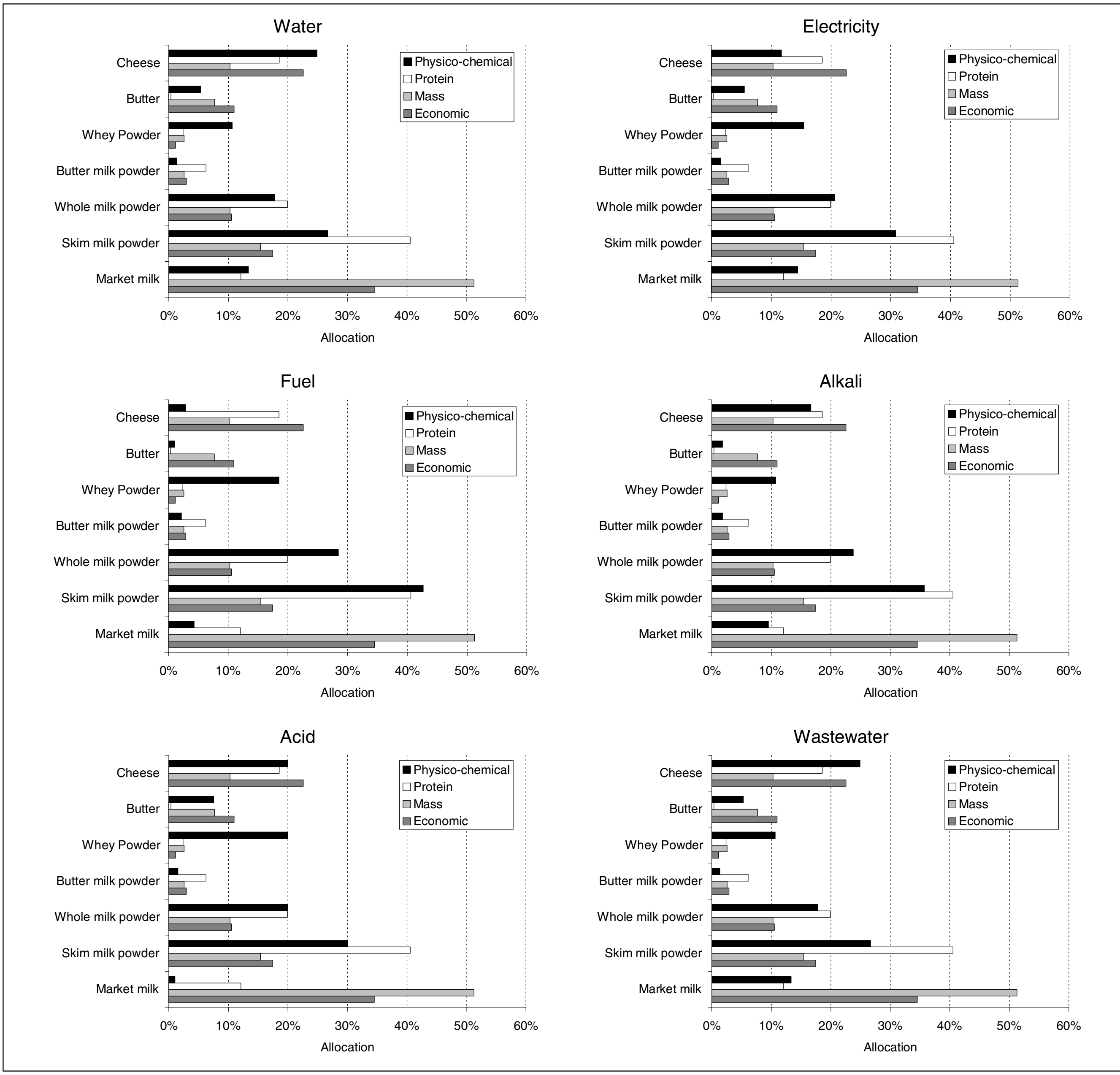

Fig. 2: Comparison of allocation methods for different resource inputs and wastewater for a model dairy manufacturing plant. Technical refers to the allocation using the matrix. WMP = whole milk powder; SMP = skim milk powder; WP = whey powder; BMP = butter milk powder

methods. Physico-chemical allocation avoids large errors that may be introduced through economic allocation provided that an industry specific physico-chemical allocation matrix can be generated. Appropriate allocation appears to be a more important issue than truncation errors that occur when defining the system boundary in process-based LCA studies. We propose that physico-chemical allocation should be used wherever necessary for allocating intra-industry sectoral flows (i.e. mass, process energy and emissions), while economic allocation using input-output technique may reflect inter-industry sectoral flows in the absence of more detailed technological information. It is recommended that similar industry-specific physico-chemical allocation matrices be developed for other industrial sectors: for example, agriculture (e.g. the meat industry); construction (e.g. sand, gravel and other construction materials); mining (e.g. gold and lead) and petrochemical industries (e.g. automotive fuels). The allocation matrices are essentially technology matrices within an industrial sector and could ultimately be coupled with input-output analysis to accurately quantify resources for individual products.

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